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6. AUTHORS M.G. Mungal		
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16 SEP 1998

**Final Report for AASERT Grant F49620-95-1-0448**  
**01 July 1995 - 30 June 1998**

M. G. Mungal  
Mechanical Engineering Department  
Stanford University  
Stanford, CA 94305-3032

**Abstract:**

This work was aimed at obtaining a more fundamental understanding of mixing and combustion in supersonic flows. Advanced laser-based techniques for measurements in an existing supersonic shear layer facility were primarily used. The main scientific question addressed was a comparison of the similarities and differences between mixing and reaction when compressibility plays a significant role. To this end, Particle Image Velocimetry (PIV) was used to obtain detailed, whole-field velocity measurements under a range of compressibility conditions. These measurements are complementary to earlier measurements of scalar concentrations in similar flows. New observations concerning the nature of the instantaneous velocity and vorticity fields were made as a function of compressibility. In addition, Planar Laser Mie Scattering is used to obtain structure velocity measurements for comparison with the actual fluid velocities.

**Accomplishments:**

Our experiments were conducted in a large-scale, dual-stream facility in which the high-speed stream is supersonic with the capability of vitiation heating to stagnation temperatures of under 2000K. The low-speed stream is subsonic, with a stagnation temperature of 300K. Our design modifies both flow trains to divert part of the flow into the seeders which use fine alumina as the seed material; this flow is then recombined with the main flow before entering the test section. We have demonstrated the very satisfactory performance of this high-flow tunnel for PIV measurements. In addition, double-pulse scalar velocimetry is performed for comparison with the PIV results.

We have obtained detailed PIV images in compressible flows during this contract, providing the first such measurements of the planar velocity field. Owing to the higher degree of three dimensionality, we have had to implement a spinning mirror as part of the PIV setup to eliminate data dropout with data yields in excess of 98%. Convective Mach numbers investigated were 0.28 (low compressibility), 0.63 (moderate compressibility) and 0.79 (high compressibility).

We were able to demonstrate that our PIV measurements recover the same values for Reynolds stresses as found in earlier LDV studies of compressible mixing layers, thus implying accurate measurement of the velocity field. Some of our main findings concern the wave-like appearance of the instantaneous velocity field, the variation in the instantaneous transverse velocities in the layer under compressible conditions where we observe significant perturbations to the error-function mean profile with even local minima within the layer and considerable streamwise meandering with wavelengths which decrease with compressibility. We are also able to observe steep velocity gradients at the instantaneous sonic line, suggesting that the flow would be receptive to disturbances from the lab frame. The vorticity is seen to be sheet-like in nature and mimics the scalar images seen in previous studies. Additional data includes the interaction of a shock with the mixing layer to determine the changes that are produced. We are presently performing a thorough and final comparison of the velocity and vorticity fields among the various cases to highlight the effects of compressibility upon turbulent mixing; these results will be

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**AUGMENTATION AWARDS FOR SCIENCE & ENGINEERING RESEARCH TRAINING (AASERT)**  
**REPORTING FORM**

The Department of Defense (DoD) requires certain information to evaluate the effectiveness of the AASERT Program. By accepting this Grant which bestows the AASERT funds, the Grantee agrees to provide 1) a brief (not to exceed one page) narrative technical report of the research training activities of the AASERT-funded student(s) and 2) the information requested below. This information should be provided to the Government's technical point of contact by each annual anniversary of the AASERT award date.

1. Grantee identification data: (R&T and Grant numbers found on Page 1 of Grant)

a. Stanford University  
University Name

b. F49620-95-1-0448  
Grant Number

c. \_\_\_\_\_  
R&T Number

d. M. G. Mungal  
P.I. Name

e. From: 1 July 1995 To: 30 June 1998  
AASERT Reporting Period

NOTE: Grant to which AASERT award is attached is referred to hereafter as "Parent Agreement".

2. Total funding of the Parent Agreement and the number of full-time equivalent graduate students (FTEGS) supported by the Parent Agreement during the 12-month period prior to the AASERT award date.

a. Funding: \$ 196,429  
b. Number FTEGS: 4

3. Total funding of the Parent Agreement and the number of FTEGS supported by the Parent Agreement during the current 12-month reporting period.

a. Funding: \$ 0  
b. Number FTEGS: 0

4. Total AASERT funding and the number of FTEGS and undergraduate students (UGS) supported by AASERT funds during the current 12-month reporting period.

a. Funding: \$ 40,000  
b. Number FTEGS: 1  
c. Number UGS: 0

**VERIFICATION STATEMENT:** I hereby verify that all students supported by the AASERT award are U.S. citizens.

M. G. Mungal  
Principal Investigator

September 9, 1998

Date

## Principal Investigator Annual Data Collection (PIADC) Survey Form

NOTE: If there is insufficient space on this survey to meet your data submission, please submit additional data in the same format as identified below.

### PI DATA

Name(last,First,MI) Mungal, M.G.

#### **AFOSR USE ONLY**

Project/Subarea

Institution: Stanford University

/

Contract/Grant No.: AASERT F49620-95-0448

NX       

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### NUMBER OF CONTRACT/GRANT CO-INVESTIGATORS

Faculty 1

Post doctorates       

Graduate Student 1 Other       

### PUBLICATIONS RELATED TO AFOREMENTIONED CONTRACT/GRANT

NOTE: List names in the following format: Last Name, First Name, MI

Include: Articles in peer reviewed publications, journals, book chapters, and editorships of books.

Do not include: Unreviewed proceedings and reports, abstracts, "Scientific American" type articles, or articles that are not primary reports of new data, and articles submitted or accepted for publication, but with a publication date outside the stated time frame.

Name of Journal, Book, etc: none

Title of Article:       

Author(s):       

Publisher (if applicable):       

Vol:        Page(s):        Month Published:        Year Published:       

Name of Journal, Book, etc:       

Title of Article:       

Author(s):       

Publisher (if applicable)

Volume:        Page(s):        Month Published:        Year Published:

**HONORS/AWARDS RECEIVED DURING CONTRACT/GRANT LIFETIME**

**Include:** All honors and awards received during the lifetime of the contract or grant, and any life achievement honors such as (Nobel prize, honorary doctorates, and society fellowships) prior to this contract or grant

**Do Not Include:** Honors and awards unrelated to the scientific field covered by the contract/grant.

Honor/Award      none      Year Received: \_\_\_\_\_

Honor/Award Recipient(s): \_\_\_\_\_

Awarding Organization: \_\_\_\_\_

become the Ph.D. thesis of Mr. W. D. Urban, and should be formally completed by December 1998.

Finally, under separate funding from the NSF we have been able to perform a companion study where sub-boundary layer disturbances have been used to perturb the mixing layer. Using PIV we have been able to compare those results to the present results and show conclusively that streamwise vortices are formed that lead to profound changes in the layer structure.

The following papers have been presented during the course of this work:

1. W. D. Urban & M. G. Mungal (1997), "Planar Velocity Measurements in Compressible Mixing Layers", AIAA-97-0757, 35th AIAA Aerospace Sciences Meeting, Reno, NV.
2. W. D. Urban & M. G. Mungal (1997), "Fluid and Structure Velocity Measurements in Compressible Mixing Layers", FEDSM97-3155, ASME Fluids Engineering Division Summer Meeting, Vancouver, British Columbia, June 22-26, 1997.
3. W. D. Urban & M. G. Mungal (1997) "Velocity Field Measurements in Compressible Mixing Layers", Bull. Amer. Phys. Soc., 42 (11), 2210, Nov. 1997.
4. W. D. Urban, S. Watanabe & M. G. Mungal (1998), "Velocity Field of the Planar Shear Layer: Compressibility Effects", AIAA-98-0697, 36th AIAA Aerospace Sciences Meeting, Reno, NV.
5. W. D. Urban & M. G. Mungal (1998), "A PIV Study of Compressible Shear Layers", Ninth International Symposium on Applications of Laser Techniques to Fluid Mechanics, 13-16 July 1998, Lisbon, Portugal.

#### **Personnel:**

Mr. William D. Urban is the graduate student involved in the work described here. This work constitutes the major part of his Ph.D. studies, in co-sponsorship with the NSF. He is in the process of writing up his Ph.D. dissertation which will be defended in the fall of 1998. Archival publications will then be forthcoming.